Modifications on nucleon parameters at finite temperature

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Abstract

Taking into account the additional operators coming up at finite temperature, we investigate the mass and residue of the nucleon in the framework of thermal QCD sum rules. We observe that the mass and residue of the nucleon are initially insusceptible to increase of temperature, however after a certain temperature, they start to fall increasing the temperature.

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1 Introduction

The investigation of the modifications on the hadronic parameters such as masses, decay constants, widths and coupling constants, etc. at finite temperature is one of the important research areas of thermal QCD. The theoretical determinations of these modifications provide us with the better understanding of the properties of hot and dense QCD matter produced by the heavy ion collision experiments. Such studies can also help us in understanding the internal structures of the dense astrophysical objects like neutron stars.

In order to perform the theoretical studies on the hadronic parameters at finite temperature, some non-perturbative approaches are required. One of the most applicable and powerful methods in this context is QCD sum rule approach. This method at zero temperature has been first proposed in [1, 2], which was based on the operator product expansion (OPE) and quark-hadron duality assumption. This approach has been extended to finite temperatures in [3]. At finite temperature, the Lorentz invariance is broken due to the residual O(3) symmetry. In order to restore the Lorentz invariance, the four-vector velocity of the medium is introduced. As a result, some new operators appear in the Wilson expansion [4–6] and the vacuum condensates are replaced by their thermal expectation values.

In the literature, there are a lot of studies on the investigation of the hadronic parameters at finite temperature, but only a few of them have been devoted to the analysis of the modifications of parameters such as the mass and residue of the nucleon at finite temperature [7–14]. In [7], the nucleon mass and its residue as a function of the temperature have been investigated using the correlation function of a three-quark current with the help of the virial expansion. It has been obtained that the nucleon mass rapidly rises with temperature, while its residue falls with increasing temperature. In [8], the nucleon mass at finite temperature has been analyzed via the QCD sum rules method. The authors have used Ioffe current and demonstrated that the nucleon mass is decrease with temperature. In [9], the nucleon mass shift at finite temperature has been calculated using chiral counting arguments and a virial expansion. It has been shown that the nucleon's mass decreases with increasing the temperature up to roughly $T = 90\ MeV$, but after this point the mass starts to rapidly increase with increasing the temperature. In [10], the authors have obtained the spectral representation for the nucleon and given the expressions of the nucleon mass and its residue with respect to the temperature using Ioffe current by QCD sum rules approach. In this paper, S. Mallik and S. Sarkar have realized that the obtained results support the earlier results in [7]. In [11], the nucleon mass at finite temperature has been calculated using Bethe-Salpeter equation (BSE) by observing that the nucleon mass decreases smoothly with temperature. In [12], the nucleon properties below the critical point temperature have been investigated. The author has solved the field equations in the mean-field approximation using the effective mesonic potential at finite temperature and found that the nucleon mass increases up to $\frac{4}{5}T_c\ MeV$ then decreases near to the critical temperature T_c. In [13], the nucleon mass at nonzero temperature is investigated within the framework of the linear σ model. It has been shown that the nucleon mass increases monotonically with the temperature T. In [14], the nucleon properties at finite temperature have been analyzed in the linear sigma model, in which the higher-order mesonic interactions up to the eighth-order interactions are included. It has been found that the nucleon mass increases with increasing of temperature.

In the present study, we calculate the mass and residue of the nucleon at finite temperature using the most general form of the interpolating current in the framework of thermal QCD sum rules. In our calculations, we use the thermal light quark propagator in coordinate space containing the perturbative and non-perturbative contributions as well as additional operators rising at finite temperature. We evaluate the two-point thermal correlation function first in coordinate space then transform the calculations to momentum space. In order to perform the numerical analysis, we firstly determine the working regions of the auxiliary parameters entering the calculations and use the fermionic and gluonic part of the energy density as well as the temperature-dependent light quark and gluon condensates together with the temperature-dependent continuum threshold. We see that the Ioffe current which is a special case of the general current ($t = -1$) remains roughly out of the reliable region.

The outline of the paper is as follows: In the next section, taking into account the additional operators arising at finite temperature, we derive thermal QCD sum rules for the mass and residue of the nucleon. The last section is devoted to the numerical analyses of the sum rules and comparison of the results with those existing in the literature.

2 Thermal QCD sum rules for the mass and residue of the nucleon

This section is dedicated to the details of the calculations of the mass and residue of the nucleon at finite temperature using thermal QCD sum rules. The starting point is to consider the following two-point thermal correlation function:

$$\Pi(p,T) = i\int d^4x\ e^{ip\cdot x} Tr\Big(\rho\ \mathcal{T}\Big(J(x)\bar{J}(0)\Big)\Big), \tag{1}$$

where p is the four momentum of the nucleon, $\rho = e^{-\beta H}/Tre^{-\beta H}$ is the thermal density matrix of QCD at temperature $T = 1/\beta$, H is the QCD Hamiltonian and $\mathcal{T}$ indicates the time ordering product. The most general form of the interpolating current for the nucleon can be written as

$$J(x) = 2\epsilon_{abc}\sum_{i=1}^{2}\Big[q_1^{T,a}(x)CA_1^i q_2^b(x)\Big]A_2^i q_1^c(x), \tag{2}$$

where a, b, c are color indices, C is the charge conjugation operator, $A_1^1 = I$, $A_1^2 = A_2^1 = \gamma_5$ and $A_2^2 = t$, with t is being an arbitrary auxiliary parameter and $t = -1$ corresponds to the Ioffe current (see [15–18] for detailed discussions on the nucleon current). Considering the isospin symmetry, we will deal with the proton ($q_1 = u$ and $q_2 = d$) in the following.

According to the general philosophy of the QCD sum rule approach, the above mentioned thermal correlation function can be calculated in two different ways. First, in terms of the hadronic parameters called the hadronic side and the second, in terms of QCD degrees of freedom called the OPE side. Equating the hadronic and OPE sides of the correlation function, the sum rules for the mass and residue of the nucleon at finite temperature are

obtained. Applying a Borel transformation and continuum subtraction to both sides of the obtained sum rules, the contributions of the higher states and continuum are suppressed.

In order to obtain the hadronic side of the correlation function, we insert a complete set of the nucleon state with the same quantum numbers as the interpolating current into the thermal correlation function. This side can be written in terms of different structures as

$$\begin{aligned}\Pi^{Had}(p,T) &= \Pi_p^{Had}(p^2,p_0,T)\,\not{p}+\Pi_u^{Had}(p^2,p_0,T)\,\not{u}\\ &+ \Pi_{p,u}^{Had}(p^2,p_0,T)\,\not{p}\,\not{u}+\Pi_S^{Had}(p^2,p_0,T)I,\end{aligned}\tag{3}$$

where u_μ is the four-velocity of the heat bath, p_0 is the energy of the quasi-particle and I is the unit matrix. In the rest frame of the heat bath, $u_\mu=(1,0,0,0)$ and $u^2=1$. To obtain the mass and residue of the nucleon, we use the structure $\not{p}$ whose coefficient is

$$\Pi_p^{Had}(p^2,p_0,T) = -\lambda_N^2(T)\frac{1}{p^2-m_N^2(T)},\tag{4}$$

where $m_N(T)$ is the nucleon mass and $\lambda_N(T)$ is its residue at finite temperature. After performing the Borel transformation with respect to p^2 in Eq. (4), the final form of the coefficient of $\not{p}$ on hadronic side is obtained as

$$\hat{B}\Pi_p^{Had}(p_0,T)=-\lambda_N^2(T)e^{-m_N^2(T)/M^2},\tag{5}$$

where M^2 is the Borel mass parameter.

On the other hand, the OPE side of the thermal correlation function is calculated via OPE in deep Euclidean region. The correlation function on this side can also be written in terms of different structures as

$$\begin{aligned}\Pi^{OPE}(p,T) &= \Pi_p^{OPE}(p^2,p_0,T)\,\not{p}+\Pi_u^{OPE}(p^2,p_0,T)\,\not{u}\\ &+ \Pi_{p,u}^{OPE}(p^2,p_0,T)\,\not{p}\,\not{u}+\Pi_S^{OPE}(p^2,p_0,T)I.\end{aligned}\tag{6}$$

To calculate the OPE side, we use the explicit form of the interpolating current in the thermal correlation function and contract out all quark pairs using the Wick's theorem. As a result, we get

$$\begin{aligned}\Pi^{OPE}(p,T) &= 4i\epsilon_{abc}\epsilon_{a'b'c'}\int d^4xe^{ipx}\Bigg\langle\Bigg\{\Bigg(\gamma_5 S_u^{cb'}(x)S_d^{\prime ba'}(x)S_u^{ac'}(x)\gamma_5\\ &- \gamma_5 S_u^{cc'}(x)\gamma_5 Tr\Big[S_u^{ab'}(x)S_d^{\prime ba'}(x)\Big]\Bigg)+t\Bigg(\gamma_5 S_u^{cb'}(x)\gamma_5 S_d^{\prime ba'}(x)S_u^{ac'}(x)\\ &+ S_u^{cb'}(x)S_d^{\prime ba'}(x)\gamma_5 S_u^{ac'}(x)\gamma_5-\gamma_5 S_u^{cc'}(x)Tr\Big[S_u^{ab'}(x)\gamma_5 S_d^{\prime ba'}(x)\Big]\\ &- S_u^{cc'}(x)\gamma_5 Tr\Big[S_u^{ab'}(x)S_d^{\prime ba'}(x)\gamma_5\Big]\Bigg)+t^2\Bigg(S_u^{cb'}(x)\gamma_5 S_d^{\prime ba'}(x)\gamma_5 S_u^{ac'}(x)\\ &- S_u^{cc'}(x)Tr\Big[S_d^{ba'}(x)\gamma_5 S_u^{\prime ab'}(x)\gamma_5\Big]\Bigg)\Bigg\}\Bigg\rangle_T,\end{aligned}\tag{7}$$

where $S' = CS^TC$, $S_q(x)$ is the thermal light quark propagator and $Tr[...]$ stands for the trace of gamma matrices. The thermal light quark propagator is given as

$$
\begin{aligned}
S_q^{ij}(x) &= i\frac{\not{x}}{2\pi^2x^4}\delta_{ij} - \frac{m_q}{4\pi^2x^2}\delta_{ij} - \frac{\langle\bar{q}q\rangle}{12}\delta_{ij} - \frac{x^2}{192}m_0^2\langle\bar{q}q\rangle\Big[1 - i\frac{m_q}{6}\not{x}\Big]\delta_{ij} \\
&+ \frac{i}{3}\Big[\not{x}\Big(\frac{m_q}{16}\langle\bar{q}q\rangle - \frac{1}{12}\langle u\Theta^f u\rangle\Big) + \frac{1}{3}\Big(u\cdot x\,\not{u}\langle u\Theta^f u\rangle\Big)\Big]\delta_{ij} \\
&- \frac{ig_s\lambda_A^{ij}}{32\pi^2x^2}G_{\mu\nu}^A\Big(\not{x}\sigma^{\mu\nu} + \sigma^{\mu\nu}\not{x}\Big),
\end{aligned}
\tag{8}
$$

where m_q is the light quark mass, $\langle\bar{q}q\rangle$ is the temperature-dependent quark condensate, $G_{\mu\nu}^A$ is the external gluon field at finite temperature, $\Theta_{\mu\nu}^f$ is the fermionic part of the energy momentum tensor and λ_A^{ij} are Gell-Mann matrices with $\lambda_A^{ij}\lambda_A^{kl} = \frac{1}{2}(\delta_{il}\delta_{jk} - \frac{1}{N_c}\delta_{ij}\delta_{kl})$. We insert the above quark propagator into Eq. (7) and perform the four-integral over x to go to the momentum space using Fourier transformations. To suppress the contribution of the higher states and continuum, a Borel transformation with respect to the p^2 as well as continuum subtraction are applied. We also use

$$
\begin{aligned}
\langle Tr^c G_{\alpha\beta}G_{\mu\nu}\rangle &= \frac{1}{24}(g_{\alpha\mu}g_{\beta\nu} - g_{\alpha\nu}g_{\beta\mu})\langle G_{\lambda\sigma}^a G^{a\lambda\sigma}\rangle \\
&+ \frac{1}{6}\Big[g_{\alpha\mu}g_{\beta\nu} - g_{\alpha\nu}g_{\beta\mu} - 2(u_\alpha u_\mu g_{\beta\nu} - u_\alpha u_\nu g_{\beta\mu} - u_\beta u_\mu g_{\alpha\nu} + u_\beta u_\nu g_{\alpha\mu})\Big] \\
&\times \langle u^\lambda \Theta_{\lambda\sigma}^g u^\sigma\rangle
\end{aligned}
\tag{9}
$$

to relate the two-gluon condensate to the gluonic part of the energy momentum tensor. Here $\Theta_{\lambda\sigma}^g$ is the traceless gluonic part of the stress-tensor of the QCD. After lengthy calculations, the Π_p^{OPE} function in Borel scheme up to linear terms in light quark mass is obtained as

$$
\begin{aligned}
\hat{B}\Pi_p^{OPE}(p_0,T) &= \frac{5+2t+5t^2}{512\pi^4}\int_{(2m_u+m_d)^2}^{s_0(T)} ds\exp\Big(-\frac{s}{M^2}\Big)s^2 \\
&+ \frac{\langle\bar{q}q\rangle}{96\pi^2}\Big[m_0^2\Big((-23-2t+13t^2)m_d + 2(-11-8t+7t^2)m_u\Big) \\
&+ \Big((51+6t-21t^2)m_d - 18(-3-2t+t^2)m_u\Big)\int_{(2m_u+m_d)^2}^{s_0(T)} ds\exp\Big(-\frac{s}{M^2}\Big)\Big] \\
&+ \frac{\langle u\Theta^f u\rangle}{72\pi^2}(5+2t+5t^2)\Big[8p_0^2 - 5\int_{(2m_u+m_d)^2}^{s_0(T)} ds\exp\Big(-\frac{s}{M^2}\Big)\Big] \\
&- \frac{\alpha_s\langle u\Theta^g u\rangle}{192\pi^3N_c}(5+2t+5t^2)(-1+N_c)\Big[4p_0^2 - \int_{(2m_u+m_d)^2}^{s_0(T)} ds\exp\Big(-\frac{s}{M^2}\Big)\Big] \\
&- \frac{3\langle\alpha_s G^2\rangle}{256\pi^3N_c}(5+2t+5t^2)(-1+N_c)\int_{(2m_u+m_d)^2}^{s_0(T)} ds\exp\Big(-\frac{s}{M^2}\Big) \\
&- \langle\bar{q}q\rangle^2\Big[-\frac{(-5-2t+7t^2)(m_0^2-2M^2)}{12M^2}\Big] \\
&+ \frac{\langle\bar{q}q\rangle\langle u\Theta^f u\rangle}{27M^6}\Big\{-2m_0^2\Big((1+t^2)m_d + 2(2+t+2t^2)m_u\Big)(M^2+2p_0^2)
\end{aligned}
$$

$$
\begin{aligned}
&+ \quad 3M^2\Bigg[m_d\Big((-7-2t+5t^2)M^2+8(1+t^2)p_0^2\Big)\\
&+ \quad 2m_u\Big(M^2+7t^2M^2+8(2+t+2t^2)p_0^2\Big)\Bigg]\Bigg\}\\
&+ \quad \frac{\alpha_s\langle\bar{q}q\rangle\langle u\Theta^g u\rangle}{144\pi N_c M^6}\Bigg[\Big((1+t)^2m_d-2(3+2t+3t^2)m_u\Big)(-1+N_c)\\
&\times \quad \Big(m_0^2(3M^2-2p_0^2)+3M^2(-5M^2+4p_0^2)\Big)\Bigg]\\
&+ \quad \frac{\langle\bar{q}q\rangle\langle\alpha_s G^2\rangle}{192\pi N_c M^4}\Big[(1+t)^2m_d-2(3+2t+3t^2)m_u\Big](4m_0^2-15M^2)(-1+N_c)\\
&- \quad \frac{\alpha_s\langle u\Theta^f u\rangle\langle u\Theta^g u\rangle}{36\pi N_c M^4}(-1+N_c)\Big[(21+2t+21t^2)M^2-4(7+6t+7t^2)p_0^2\Big]\\
&- \quad \frac{\langle\alpha_s G^2\rangle\langle u\Theta^f u\rangle}{144\pi N_c M^4}(-1+N_c)\Big[(71+22t+71t^2)M^2-8(1+t)^2p_0^2\Big]\\
&+ \quad \frac{2\langle u\Theta^f u\rangle^2}{9M^2}(5+2t+5t^2) \qquad (10)
\end{aligned}
$$

Finally, matching the hadronic and OPE sides of the correlation function, the sum rule for the residue of the nucleon at finite temperature is obtained as:

$$
-\lambda_N^2(T)e^{-m_N^2(T)/M^2}=\hat{B}\Pi_p^{OPE}(p_0,T). \qquad (11)
$$

To find the mass of nucleon from above sum rule, we apply derivative with respect to $1/M^2$ to both sides of Eq. (11) and divide by itself. Eventually, the mass of nucleon at finite temperature is obtained as:

$$
m_N^2(T)=\frac{\frac{\partial}{\partial(-\frac{1}{M^2})}\Big[\hat{B}\Pi_p^{OPE}(p_0,T)\Big]}{\hat{B}\Pi_p^{OPE}(p_0,T)}. \qquad (12)
$$

3 Numerical results

In this section, we present numerical analysis on the mass and residue of the nucleon at finite temperature obtained via thermal QCD sum rules. We determine how the results at finite temperature shift from those obtained at zero temperature. For this aim, we use the input parameters given in Table 1.

Besides these input parameters, we need to know the temperature dependence of the quark and gluon condensates, the thermal average of the energy density and the temperature-dependent expression of continuum threshold.

In this study, for the temperature-dependent quark condensate we use the parametrization given in [23], which can be fitted to the following function up to the quark-gluon deconfinement at a critical temperature $T_c \simeq 197\ MeV$:

$$
\langle\bar{q}q\rangle=\frac{\langle 0|\bar{q}q|0\rangle}{1+e^{18.10042(1.84692T^2+4.99216T-1)}}, \qquad (13)
$$

Parameters	Values
p_0	$1\ GeV$
m_u	$(2.3^{+0.7}_{-0.5})\ MeV$
m_d	$(4.8^{+0.5}_{-0.3})\ MeV$
m_0^2	$(0.8 \pm 0.2)\ GeV^2$
$\langle 0 \vert \bar{q}q \vert 0 \rangle_{q=u,d}$	$-(0.24 \pm 0.01)^3\ GeV^3$
$\langle 0 \mid \frac{1}{\pi}\alpha_s G^2 \mid 0 \rangle$	$(0.012 \pm 0.004)\ GeV^4$

Table 1: The values of input parameters used in numerical calculations [19–22].

where $\langle 0|\bar{q}q|0\rangle$ denotes the light-quark condensate in vacuum. The above parametrization is consistent with the lattice QCD results [24, 25].

For the gluonic and fermionic parts of the energy density we use the results obtained from lattice QCD at higher temperatures. In the rest frame of the heat bath, the results of some quantities obtained using lattice QCD in [26] are well fitted by the help of the following parametrization:

$$\langle \Theta^g_{00} \rangle = \langle \Theta^f_{00} \rangle = T^4 e^{(113.867T^2 - 12.190T)} - 10.141T^5, \tag{14}$$

where this is valid for $T \geq 130\ MeV$.

We take the temperature-dependent continuum threshold as

$$s_0(T) \simeq s_0 \frac{\langle \bar{q}q \rangle}{\langle 0|\bar{q}q|0\rangle}, \tag{15}$$

where s_0 is the continuum threshold at zero temperature. The temperature-dependent gluon condensate corresponding to $T_c \simeq 197\ MeV$ is also given as [27]

$$\langle G^2 \rangle = \langle 0|G^2|0\rangle \Big[1 - 1.65(\frac{T}{T_c})^{8.735} + 0.04967(\frac{T}{T_c})^{0.7211}\Big], \tag{16}$$

where $\langle 0|G^2|0\rangle$ stands for the gluon condensate in vacuum.

The next step is to determine the working regions for three auxiliary parameters, namely Borel mass parameter M^2, the continuum threshold s_0 and mixing parameter t. It is expected that the physical quantities are roughly independent of these auxiliary parameters in their working regions.

The working region for the Borel mass parameter is found demanding that the contributions of the higher states and continuum are adequately suppressed as well as the contributions of the higher dimensional operators are small. These conditions lead to the interval $0.8\ GeV^2 \leqslant M^2 \leqslant 1.2\ GeV^2$ for the Borel mass parameter. The continuum threshold is not utterly arbitrary but it is associated with the energy of the first excited state with the same quantum numbers as the chosen interpolating current. From our numerical analysis, we obtain the interval $s_0 = (1.5 - 2.0)\ GeV^2$ for the continuum threshold. In order to determine the working region of the mixing parameter t, we need to investigate the dependence of the physical quantities on t in the whole range $-\infty \leq t \leq \infty$. For this purpose, we plot the mass and residue of the nucleon with respect to $x = cos\theta$, where $t = tan\theta$,

at fixed values of the continuum threshold s_0 for Borel mass parameter $M^2 = 1\ GeV^2$ at $T = 0$ in figure 1. From this figure, we see that the dependences of the mass and residue on this parameter are relatively weak in the intervals $-0.6 \leq x \leq -0.2$ and $0.2 \leq x \leq 0.6$. Also, we realize that the Ioffe current which corresponds to $x = -0.71$ remains out of the reliable region.

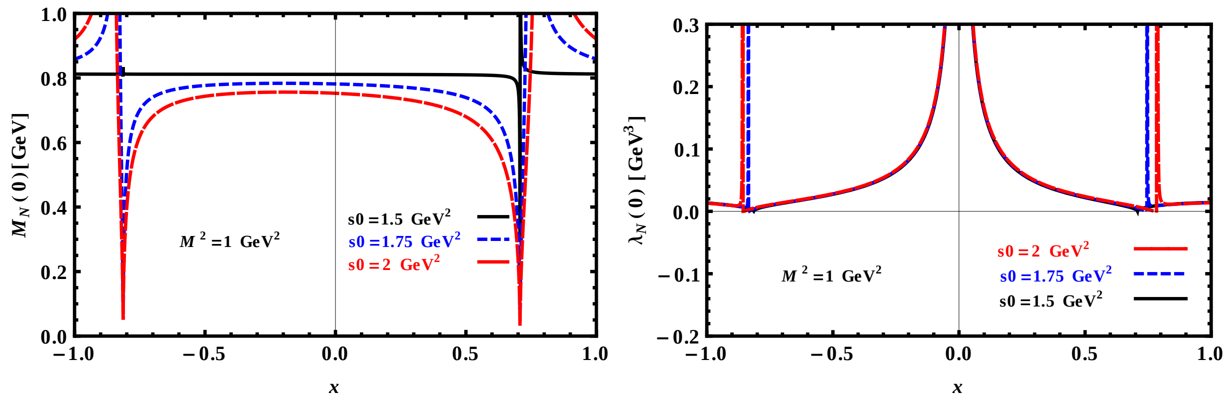

Figure 1: The mass and residue of the nucleon as a function of x at $M^2 = 1\ GeV^2$, $T = 0$ and at different fixed values of s_0.

To see how our results depend on the Borel mass parameter in the above determined working regions, we plot the mass and residue of the nucleon at zero temperature with respect to Borel mass parameter M^2 at different fixed values of x and s_0 in figure 2. This figure depicts that the values of the physical quantities under consideration depend weakly on the Borel parameters in its working region, $0.8\ GeV^2 \leqslant M^2 \leqslant 1.2\ GeV^2$.

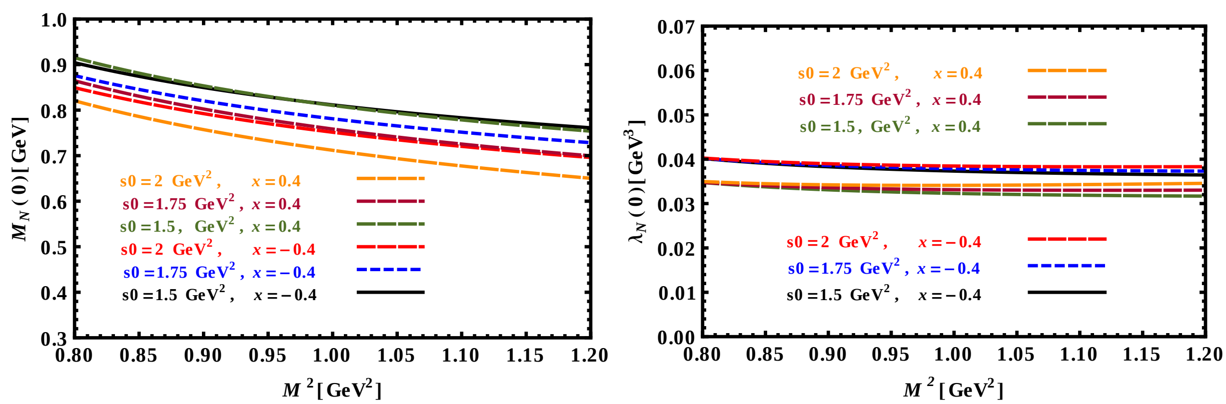

Figure 2: The mass and residue of the nucleon as a function of M^2 at $T = 0$ and at different fixed values of s_0 and x.

In further analysis, the dependence of the mass and residue of the nucleon on the temperature are shown in figure 3 at different values of the auxiliary parameters in their working regions. With a quick glance at this figure, we observe that the mass and residue of the nucleon remain approximately unchanged up to $T \cong 0.15\ GeV$, after which they

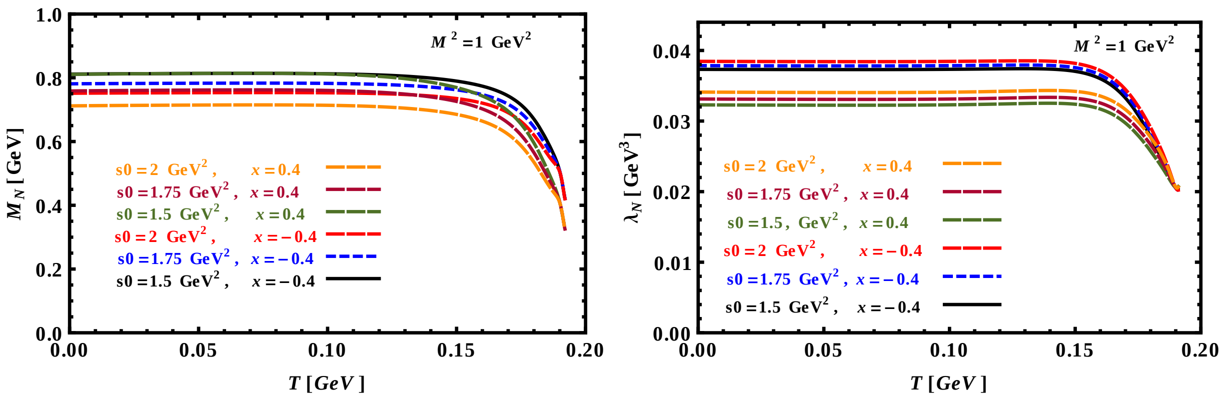

Figure 3: The mass and residue of the nucleon as a function of temperature at $M^2 = 1\,GeV^2$ and at different fixed values of s_0 and x.

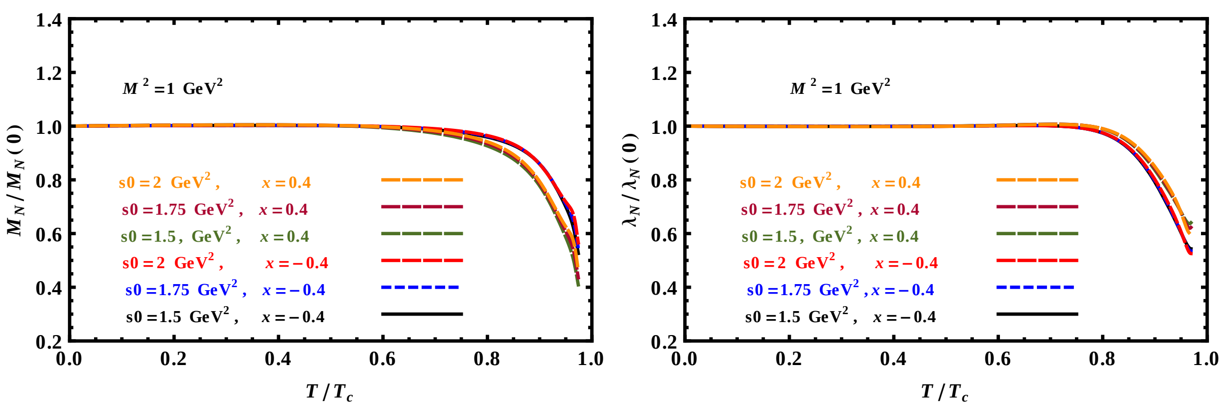

Figure 4: $M_N/M_N(0)$ and $\lambda_N/\lambda_N(0)$ as a function of T/T_c at $M^2 = 1\,GeV$ and at different fixed values of s_0 and x.

start to diminish increasing the temperature. Near to the critical temperature, the mass of the nucleon falls to roughly 42% of its values at zero temperature while the residue reaches roughly to 60% of its value at zero temperature.

To better see the deviations of the mass and residue of the nucleon from their vacuum values, we show the dependence of the ratios $M_N/M_N(0)$ and $\lambda_N/\lambda_N(0)$ to T/T_c in figure 4. When we compare these behaviors in terms of the temperature with those of existing results in the literature, we see that as far as the residue is concerned our results support the behaviors obtained in [7, 10] for the residue with respect to the temperature at whole region. In the case of mass, our results on the variation of the mass of the nucleon are in agreement with those of [8, 11]. Although are also in good agreements at low temperatures, our results on the behavior of the mass with respect to temperature are in contradiction with those of [7, 9, 10, 12–14] at high temperatures.

To summarize, we calculated the mass and residue of the nucleon at finite temperature in the framework of the two-point thermal QCD sum rules. We used the general form of the nucleon's interpolating current and found the working regions of auxiliary parameters

entering the calculations. It has been obtained that the Ioffe current remains out of the reliable region for the general mixing parameter entering the general form of the interpolating current. We have also used the temperature dependence of the quark and gluon condensates, the thermal average of the energy density and the temperature-dependent expression of continuum threshold to numerically analyze the sum rules for the mass and residue of the nucleon. We found that the mass and residue of the nucleon remain unchanged up to roughly 0.15 GeV. After this point, they start to decrease with increasing the temperature such that near to the critical temperature they fall down, considerably. This can be consider as a signal for transition to the quark-gluon plasma phase. We also compared the behavior of the mass and residue of the nucleon in terms of temperature obtained in the present work with those existing in the literature.

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